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Mangrove Forests in Changing Climate: A Global Overview

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Fossil records indicate that mangrove ecosystems first appeared at the beginning of the late Cretaceous period [146 to 100 million years ago (Ma)], and have considerable changes during more than 55 million years. Spreading over more than 118 countries in the tropics, subtropics and temperate regions, mangroves or coastal tidal forests now dwindle at the rate of 1-2% per year as a result of changing climate in general and sea-level rise (SLR) in particular. But the study of relative SLR is very complex; because, in most of the coastal regions exhibits five important processes - tides, subsidence, coastal erosion, sediment accretion and seal level rise which are running instantaneously. Sedimentation processes along with the mangrove's geomorphic setting of any region is an important event in responses to sea-level changes. Nevertheless, mangroves may be resilient to survive as colonizing in new areas through competitive succession and dominance as evident by its long evolutionary trend. The present study analyses the actual and predicted sea-level rise *vis-a-vis* loss of mangrove in different vulnerable coastal zones through a literature survey. South East Asia shows a gradual degradation of the forest at a higher rate compared to the rest of the world because of both natural (SLR) and anthropogenic causes (land-use changes). As a case study, the degradation of mangroves of the Sundarbans region is calculated through the NDVI approach from 2005 to 2018. The multi-temporal LISS 3 satellite data shows that the rate of degradation is around 0.113% per year. Along with the global climate change, the dependence of the populace on the mangroves ecosystem for livelihood is a common scenario in SE Asia that may cause further degradation of mangroves - a situation to strangle mangroves to have severe stress, which is somewhat minimal in the developed world due to the remote existence and sufficient conservation.

(***Key words:*** *NDVI, Resilience, Sea level rise, Sediment accretion, Sediment degradation)*

Mangrove is a shrub or small tree that grows in tidal coastal or brackish saline water of the tropical world. The Oxford dictionary mentions the word 'mangrove' since 1613, as tropical trees growing in mud or at the edge of rivers, which has roots rising above the ground. In botany, mangroves designate a family (Rhizophoraceae, order Rhizophorales) of dicotyledonous short height trees and shrubs that inhabit tidal marshes and river mouths in the coast. Chapman (1976) used the term 'mangrove' as intertidal forests or plant communities or 'mangal'. The term 'mangal' was also commonly used in French and in Portuguese to refer to both forest communities and individual plants. Duke (1992) defined a mangrove as a tree, shrub, palm, or ground fern, generally exceeding a half metre on height above mean sea level in the intertidal zone of estuarine margins. Several researchers have discoursed that plants grow in between the highest and the lowest tidal limits may be considered 'mangrove' (Aubreville, 1964; Blasco, 1977; Mandal and Bar, 2019; Naskar and Guha Bakshi, 1987; Naskar and Mandal, 1999; Tomlinson, 1986). They, sometimes, have been described as 'coastal woodlands', '*mangals*', 'tidal forests', or 'mangroves' or 'mangrove forests' (Saenger, 2002). So, in general, mangroves are salt-tolerant plant species that struggle every moment against tides as they straddle at the interface zone of the land and the sea.

The ecosystem services that mangrove forests render are staggering, including coastal protection, carbon sequestration, and nutrient processing (Barbier *et al*., 2011) and breeding and feeding grounds to invertebrates and vertebrates organisms (McLeod and Salm, 2006). Despite their unique services to human welfare, destruction such as felling or overharvesting

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of mangroves for various purposes as poles for fencing and/or housing, woods for fuel, etc. has been a common occurrence across the world, but gradually checked in the last couples of decades. Keeping aside human interference globally, mangroves are rather facing several climate-related threats due to different anthropogenic activities. Climate change impacts have gradually become an increasing threat to the existence of mangroves forests in the coastal intertidal zones that results in the dwindling of many mangroves vegetated creeks in the world (Alongi, 2002; Ellison, 2000; Field, 1995; Gilman *et al*., 2007 and 2008; Limaye *et al*., 2014; Parnetta, 1993). However, the impacts may vary on the landscape of the area as well as the activities of forest users.

Mangroves are immensely susceptible to climate change which may play a significant role for mangrove distribution to a great extent (Alongi, 2008; Gilman *et al*., 2008; Lovelock *et al*., 2007). Climate change impacts in terms of varying temperatures, rainfall, storms, and rising sea level as the major components may totally or partially destroy or disrupt the mangrove stands. Sea level rise (SLR), the biggest climate threat of the present world, increases inundation, salt stress, and erosion which may lead to mangrove retreat landward (Gilman *et al*., 2007a). However, the inundation of coastal mangrove land due to sea-level rise (SLR) may create potential resilience of these ecosystems which may be ignored in many long-term assessments of ecosystem stability or biodiversity (Zhai *et al*., 2019). In this respect, the potential resilience of mangroves, as well as other coastal vegetation, should be calculated considering surface physical sedimentation processes as well as subsurface biophysical processes (Kirwan and Megonigal, 2013; Lovelock *et al*., 2015; McKee, 2011) caused by organic matter accumulation of mangroves. The sediment accumulation, however, can be enhanced in robust aerial root structures of some mangrove species by effectively reducing water velocities resulting in settling sediments (Gedan *et al*., 2011; Krauss *et al*., 2003). As a result, in some regions, the accumulation rate may be higher than that of the rate of SLR. For example, in the Tampa Bay mangrove region of Florida (USA), the surface elevation rate was 4.2-11.0 mm yr^{-1}, as against local SLR rates of 2.6 mm yr^{-1} (Krauss *et al*., 2017).

Another important controlling factor is the cyclone or storm. Storm surges with high rainfall may cause mangrove mortality and uprooting trees may enhance land vulnerable to more erosion (FAO, 2007; McLeod and Salm, 2006). Different tropical islands already have experienced storm surge effects over the last decades. Recent reports of mangrove mortality in Australia (Duke *et al*., 2017; Lovelock *et al*., 2017), the Solomon Islands in Oceania (Albert *et al*., 2017) and Eastern Brazil Marine Ecoregion (Servino *et al*., 2018) show that mangrove mortality is increasing gradually due to increasing intensity of storms surges.

Mangroves are disappearing at a global loss rate of 1-2% per year, with substantial regional variation (FAO, 2007). It has been previously considered that 35% of the original mangrove area (136,914 km^2 in 1980) was lost by the end of the 20th century (Valiela *et al*., 2001). Mangrove loss in the early 21st century has declined from expected highs in the mid- to late 20th century (Spalding, 2012), with a global-scale remote sensing study showing that annual rates of mangrove deforestation averaged 0.2-0.7% between 2000 and 2012 (Hamilton and Casey, 2016). However, there is inadequate information on the climate change threats on mangrove ecosystems of the world. The present study, therefore, aims to analyze the impacts of climate change (sea level rise, sedimentation, storminess temperature and precipitation, etc.) on mangroves and the pattern of the resiliency of mangroves in changing climate.

Global distribution of mangroves

Mangroves are uniquely adapted to the intertidal zone in the tropics and sub-tropics ranging from mean sea level to high tide level, or in zones where moderate salinity, average temperature, and high rainfall is experienced (Alongi, 2002). Under this environment, mangroves extend more than 118 countries in the tropics, subtropics and temperate regions (Fig. 1) covering respectively 24 million hectares (Twilley *et al*., 1992), 10 million hectares (Bunt, 1992), and 14-15 million hectares (Schwamborn and Saint-Paul, 1996).

On the other hand, in general, mangroves extend six biogeographical regions like Western America and Eastern Pacific; Eastern Americas and Caribbean; Western Africa; Eastern Africa; Indo-Malaysia-Asia-Australasia and Western Pacific (Duke *et al*., 1998). In an altitudinal extension, mangroves are largely confined in between 30° north and south of the equator, with

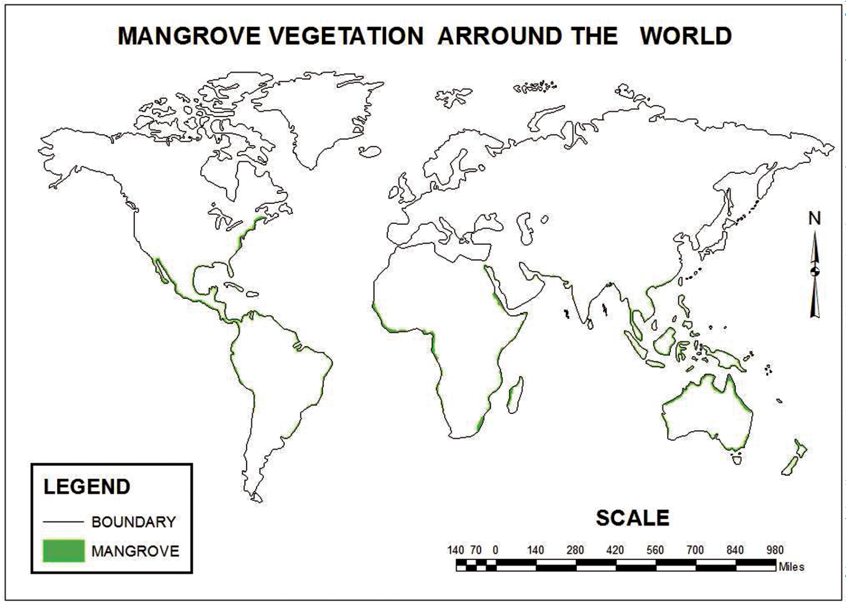

Fig. 1. *Global distribution of mangroves (after Spalding et al., 1997)*

notable additions, the north in Bermuda (32° 20' N) and Japan (31° 22' N) and to the south in Australia, New Zealand, and the east coast of South Africa. Each of these various locations is based on the existence of a tropical sea commonly known as Tethys Sea during the early Cretaceous period [146 to 100 million years ago (Ma)] separating the northern supercontinent of Laurasia (that included North America, Europe, and Asia except peninsular India) from the southern Gondwanaland (that included South America, Africa, Arabia, Madagascar, peninsular India, Australia, and Antarctica).

However, mangroves are confined to tropical or sub-tropical climates where the average monthly minimum temperature is 20°C (Chapman, 1976). This supposition is the key to searching and dispersal of mangroves through the widely accepted 'vicariance hypothesis'. This theory emphasizes that at the beginning of the late Cretaceous period (100 to 66 Ma), mangrove ecosystems first appeared and regional species diversity resulted from in situ diversification after drifting of the continents. The detailed study of the mangrove fossils by different paleontologists strongly supports this theory (Bagley and Johnson, 2014). According to the origin and evolution of mangroves is not earlier than the Cretaceous period. At the same time, however, plate tectonic theory was evolved which suggests that in the late Cretaceous period mangroves evolved around the Tethys seaway and distributed according to the movement of continents (Ellison *et al*., 1999) as suggested by the theory of plate tectonics.

Evolution of mangroves

Mangroves evolved within the Tethys Sea soon after the appearance of flowering plants, with the earliest records of Nypa in the late Cretaceous to early Palaeocene (Dolianiti, 1955) and dispersed outwards. Around 18 million years ago, eastward dispersal occurred across the Pacific and via the Panama gap into the Atlantic eastwards (Muller and Caratini, 1977) and Western dispersal occurred towards south via southern Africa to the eastern Tethys Sea (Duke, 1995).

The earliest fossil occurrence of *Rhizophora* pollen is in the Paleocene of India (Thanikaimoni and Vannucci, 1987), but it is abundant in the Eocene of Eurasia (France, Hungary, Borneo), Africa (Senegal, Gabon, Surinam), Western Australia and the Americas (British Guiana, Panama). *Rhizophora* pollen continues to be abundant in fossil deposits world-wide throughout the Miocene (Muller and Caratini, 1977) suggested that *Rhizophora* did not differentiate into modern species prior to the Oligocene. Mangrove distributions are not only influenced by long-distance dispersal but also by the geological history of the past. During more than 55 million years of mangrove evolution, there have been considerable changes to the world's oceans and landmass that greatly affects the distribution of mangroves.

Currently, there are four major continental land barriers like Africa and Euro-Asia, North and South America, and two oceanic barriers like North and South Atlantic Oceans, and the eastern Pacific Ocean which influences the dispersal of warm shallow-water marine organisms (Briggs, 1961).

The fossil record generally supports an eastern Tethys Sea origin for *Rhizophora* and perhaps *Avicennia* (Churchill, 1973; Cookson and Eisenack, 1967; Martin 1982; Stover and Evans, 1973), with a westward dispersal via the Mediterranean route. However, based on presently known fossil location it appears that *Sonneratia*, *Heritiera, Pelliciera*, and *Aegiceras* made their earliest appearances in the central Tethys Sea in the late Palaeocene to mid-Eocene (Cavagnetto and Anadón, 1995; Gruas-Cavagnetto et al., 1988). During the late Cretaceous to Palaeocene (63-55 Ma), the western Tethys Sea remained a relatively narrow waterway and western Africa was experiencing a 'wet' phase, with extensive estuarine swamp communities dominated by Nypa (Sowunmi, 1981, 1986). There was no mangrove vegetation in the Niger delta. Nypa was the first known mangrove from the late Cretaceous of Brazil (Dolianiti, 1955), which spread throughout the proto-Atlantic (Moore, 1973) after rapidly evolving.

During the late Palaeozoic and early Mesozoic eras, Pangaea was broken and the Indian subcontinent became isolated from the southern part of Pangaea, called Gondwanaland, at around 130 Ma, moved northwards, and eventually collided with Eurasia to form the Himalayas at around 40-50 Ma. The collection of mangrove fossils from the Kashmir Himalayan region also supports the origin of Himalaya from the Tethys Sea as well as mangrove habitation in the Tethys Sea.

Seeds of some tropical mangroves may even be carried out by ocean currents or tides to land on shores. The world's major ocean currents are planetary wind-driven currents. Variation of salinity and temperature resulting in variation of density are other important reasons for ocean current. Major mangrove plant lineages were separated into the Atlantic and the Indo-West Pacific (IWP) regions after the closure of the Tethys Sea and afterwards evolved in independent paths, resulting in different species assembly in each region (Duke, 1995). The subtropical high-pressure cells located above the Tethys Sea were probably responsible for developing warm ocean currents which might disperse many mangrove seeds. The present-day Gulf Stream of the North Atlantic might have some significant roles of transferring seeds to Cuba and the southern tip of Florida. The North Equatorial Current and South Equatorial Current are also responsible for migrating seeds from Europe to North America and *vice-versa*.

The facet of climate change

Climate change is considered to be a long-term change in the average weather phenomenon. This could be a change in earth's average temperature along with other elements of the atmosphere. In the geological history, earth's climate has gone through warmer and cooler periods, each lasting millions of years. Temperature is the most striking element of the earth's climate change as well as global warming. Its average surface temperature has risen to a hike of 0.8°C during the past 100 years with an average rate of 0.07°C per decade since 1880 (Hansen *et al*., 2006) and at an average rate of 0.17°C per decade since 1970 (Dahlman and Lindsey, 2020). Most of the scientists think that recent warming of surface temperature is very likely due to the burning of fossil fuels since the mid-1800s (Cazenave, 2006; Friis, 2012; IPCC, 2007, 2013).

Owing to the climate change earth's ecosystems are sustaining high irrecoverable damage in its diaphragm. Though the geographical range of species is dynamic and fluctuating, climate change is compelling a worldwide redistribution of life on earth. For aquatic (both saline and non-saline), and terrestrial species alike, the first response to changing climate is often a shift in a site, to stay within favourite environmental conditions (Lenoir and Svenning, 2015; Pecl *et al*., 2017). Consequently, the organisms of both animal and plant kingdom are adopting new methods of sustaining in the changing scenario. Halophytes like mangroves which are growing in the saline soils of tropical coastal margins are the best example of resilience and resistance to climate change. Organisms in earth's ecosystems respond to spatio-temporal patterns with changing climate for survival and thus adapt to other physical portents such as plate tectonics, ocean currents, and landform evolution (Gilman *et al*., 2008). Many common attributes of organisms in individual, population, and community level, which are related to biological and ecological changes, include tolerance to physicochemical factors, the ability to compete for limited resources, and different functional processes (Alongi, 2008). Organisms play a critical role in simplifying adaptive change (Odum and Barrett, 2004) in all ecosystems caused by both natural and anthropogenic factors. Most organisms are staying within their favoured ecological environment (Chen *et al*, 2011; Pecl *et al*., 2017) through the process of altering distributions, or redistributions occur more quickly than they have in the geological past.

Impact of climate change to the mangrove ecosystem

Climate change in the form of sea-level rise, recurring storminess, the erratic character of precipitation, increasing surface temperature, and increasing atmospheric CO_2 concentration is likely to have a significant impact on mangrove ecosystems (Ellison, 2015). Mangroves are subject to respond to both spatially and temporally to a variety of climatic changes of geological, physical, chemical, and biological phenomena. Mangroves that occupy in the transition zone between land and sea in the tropics usually face harsh environments as inundated twice a day causing submergence of land resulting in varying degrees of anoxia (Alongi, 2008; Naskar and Mandal, 1999). Mangroves are, therefore, highly adaptable and tolerant of waterlogged saline soil and exhibit a high degree of ecological stability (Alongi, 2008).

There are possibilities for mangroves to have migration to higher latitudes due to temperature rise as suggested by some scientists (Duke, 1995; Field, 1995), although their migration to poleward may be restricted by extreme cold events (Woodroffe and Grindrod, 1991). Because temperature is likely to affect some physiological events of mangroves: (i) photosynthesis, (ii) water loss, (iii) transpiration, and (iv) salt loss (Pernetta, 1993).

Furthermore, the events that may occur if mangroves are affected by increasing surface temperature (Ellison, 2000; Field *et al*., 1998) include the following: 1) species composition may change. 2) phonological patterns, including the timing of flowering and fruiting, may vary, 3) photosynthesis may occur normally, 4) productivity may increase where the temperature does not exceed an upper threshold, 5) supply of propagules may be certain.

Sea level change and mangrove health

Sea-level rise due to climate change is likely to become a serious threat and greatest challenge that the mangrove forest will bear within the upcoming future (Cahoon and Lynch, 1997; Gilman *et al*., 2007b and 2008; McLeod and Salm, 2006; Saad *et al*., 1999). During the 20th century, the rise in the sea level is measured between 12 and 22 cm. There are several other models on sea-level rise which show that the rate will be increasing at a bouncing rate and by the end of the present century, there will be a rise of about 0.18 - 0.59 m (IPCC, 2007).

For a comparative analysis of different studies regarding global sea-level rise as well as the loss of coastal land, both predicted and actual, a meta-data analysis through literature search has been done. There are various estimations of current SLR. Based on the evidence and study of mangroves in different parts of the world, the likely impact on mangroves at a different rate of SLR has been projected in Table 1. Satellite altimeter data was collected since 1993 which indicates a rise in global mean sea level (GMSL) of ~3 ± 0.4 mm yr^{-1}, resulting in more than 7 cm of total sea-level rise over the last 25 years. The latest International Panel on Climate Change (IPCC) reports predict that GMSL will rise in the range of 0.47 to 0.63 m by 2100 (IPCC, 2013). Most scientists agree that sea levels are expected to rise at least until 2100 due to present global warming (Church and White, 2011; Holgate and Woodworth, 2004). The rate is accelerating since 1990 and it is projected to increase 0.2 - 0.6 m beyond 1990 levels by 2095 (IPCC, 2007). Some other alternate models predict that it will vary between 0.5 to several meters (Carlson *et al*., 2008; Hansen *et al*., 2006; Schubert *et al*., 2006). So there is a sharp difference in data of SLR globally (Table 1).

Data variations are due to some complications in the measuring of SLR since the SLR measured by tide gauge is not uniform globally. As a result, there will be a deviation from the actual change due to the differences in local tectonic processes, coastal upliftment and subsidence, sedimentation rate, meteorology, and oceanographic factors.

Sea-level rise and mangrove sediment accretion

Mangrove vegetation can only persist if the sediment accretion rate matches the sea level rise (Smoak *et al*., 2012). Surface accretion and elevation processes have been studied at numerous mangrove sites globally. Cahoon and Hensel (2006), however, identified positive correlations between relative sea-level rise and

Table 1. *Comparative study of loss of mangroves areas (predicted and actual) due to sea-level rise (SLR) and other causes*

Region	Mangrove Area (km^2)	% of global mangroves	Rate of SLR mm yr^{-1}	Sub -region		Land Loss (km^2) Predicted (year)	Land Loss (km^2) Actual (year)	Reference
Australia	[a]10097	[a]7.3	[a]2.0-3.8	-		-	-	[a]Giri *et al*., 2011
Asia	[a]57761	[a]41.9	[a]2.0-5.4	Sundarban	Bangladesh	[b]261 (2050) [c]483 (2070) [d]478 at 12 cm SLR [e]4000 at 28 cm SLR	-	[a]Giri et al., 2011 [b&c]Mukul *et al*., 2019 [d]Barlow *et al*., 2008 [e]Loucks *et al*., 2010
					India	[f]3100 at 45 cm SLR	[f]44.04 (2001-2009)	[f]Bakshi and Panigrahi, 2015
					Total land mass		[g]8.23 (0.115%) (per year)	[g]Mandal *et al*, 2019
				Andaman & Nicobar Islands		[h]60 (2100)	[i]5.87 (1990-2018)	[h]Mitra, 2013 [i]Majumdar *et al*., 2019
				Sri Lanka	Total land mass	[j]1730 at 200 cm SLR	-	[j]Weerakkody,1996
					Negombo estuary	[k]Min: 0.53 (37.18%) -Max: 0.95 (66.83%) (2100)		[k]Perera et al., 2018
Middle East	[a]337	[a]0.3	[a]2.2-3.3	-		[l]324 at 100 cm SLR	-	[a]Giri *et al*., 2011 [l]Blankespoor *et al*., 2014
Africa	[a]27706	[a]20.1	[a]1.1-3.8	South Africa		[m]Total land mass at 28 cm SLR (2100)	[m]1.43 (2014-2018)	[a]Giri *et al*., 2011 [m]Yang *et al*., 2014
				Nile delta		[n]100 at 100 cm SLR (2100)	-	[n]Hasan, 2015
North America	a25228	[a]1.8	[a]3.0-5.1	Total land mass		[o]16682 at 200 cm SLR (2100)		[a]Giri *et al*., 2011 [o]Park *et al*., 1989
				Florida		[p&q]180 at 10 cm SLR (2100)		[p]Krauss *et al*., 2017 [q]Thomas *et al*., 2017
				[r]Texas		[r]97% of total area at 100 cm SLR.(2100) [q]1868 at 10 cm SLR (2100)		[r]Lange *et al*.,2018 [q]Thomas *et al*., 2017
Central America (Caribbean)	[a]17877	[a]13.0	[a]1-2.5	-		l3932 at 100 cm SLR	-	[a]Giri *et al*., 2011 [l]Blankespoor *et al*., 2014
South America	[a]15226	[a]11.1	[a]2-3.5			[s]7000 (2100)	-	[a]Giri *et al*., 2011 [s]Reguero, 2015

mangrove sediment accretion, which indicates that mangroves keep pace with regional relative sea-level rise, based on relatively short-term observations over time.

The rate of inorganic sediment accretion may drop exponentially as the sediment elevation increases due to gradual decreasing frequency as well as the duration of tides (Allen, 1990; Cahoon and Hensel, 2006; Woodroffe, 2002). Mangroves growing in low relief islands of the tropics are more delicate to SLR due to their sediment-deficit environments (Ellison and Stoddart, 1991; Thom, 1984; Woodroffe, 1987 and 2002). Other studies show that mangrove sediment elevation can balance a high or low level of sedimentation (Cahoon *et al*., 2003; Cahoon and Hensel, 2006). Sediment accretion increases with increased hydroperiod, including duration, frequency, and depth of inundation. In areas with very high rates of sedimentation, mangrove soil surfaces may raise at a rate that exceeds the local rate of sea-level rise, such that the terrestrial species invade landward, and progradation occurs. The increasing sediment accretion occurs through organic matter deposition as well as enhanced sediment retention with the reduced rate of flow of flood waters that would occur with higher tree productivity and root accumulation (Cahoon *et al*., 2011; McKee *et al*., 2007). So, sedimentation processes along with the mangrove's geomorphic setting of the region is an important event in responses to sea-level changes (Gilman *et al*. 2008).

Mangroves tree may dieback due to several reasons such as stresses caused by rising sea-level, erosion resulting in weakened root structures and falling of trees, increased salinity, long period of inundation along with increasing tidal frequency (Naidoo, 1983; Lewis, 2005; Ellison, 2000, 2006). Mangroves migrate new habitat as available landward through effective seedling recruitment and vegetative reproduction, with the possibility that new habitat may have different geomorphic settings such as rate of erosion, a period of inundation, and a concomitant change in salinity (Semeniuk, 1994). The species that colonize more quickly may outcompete slower colonizers through competitive succession and become more dominant.

The increasing frequency of storms and hurricanes to affect mangroves

IPCC predicted that wind intensities are likely to increase by 5 to 10% (Houghton *et al*., 2001), although there have been no reported trends observed in tropical storms, and no evidence of changes in the frequency or areas of storm formation. However, a more recent assessment predicts that tropical storms will increase in both frequency and intensity due to changing climate (Trenberth, 2005), which is likely to disturb mangroves and its ecosystems. IPCC predicts that during the 21st-century, global warming may cause an increase in tropical cyclones and precipitation intensities in some areas (Houghton *et al*., 2001; IPCC, 2007 and 2013). An increase in the frequency and intensity of strong winds cause an increase in height of storm surges when storms become more frequent or severe due to climate change (Church *et al*., 2001; Houghton *et al*., 2001; IPCC, 2013).

Storms can alter mangrove sediment elevation and budget through soil erosion, soil deposition, soil compression, soil salinity, flood inundation, and peat collapse (Smith *et al*., 1994; Woodroffe and Grime, 1999; Baldwin *et al*., 2001; Sherman *et al*., 2001; Woodroffe, 2002; Church *et al*. 2001, 2004; Cahoon *et al*., 2003; Cahoon and Hensel, 2006; Piou *et al*., 2006). Hurricanes may exacerbate the impacts of sea-level rise by uprooting trees, leaving sediment unprotected and vulnerable to erosion.

Areas suffering from mass tree mortality may also have permanent ecosystem conversion. Restoration of the ecosystem may not be possible, because seedling recruitment is unlikely to establish due to the change in sediment elevation and the associated change in hydrology (Cahoon *et al*., 2003). Roth (1997) suggests that high storm may cause to shift species proportions because they have different rates of regeneration. A tsunami can also cause severe damage to mangroves and other coastal ecosystems (Danielsen *et al*., 2005; Kathiresan and Rajendran, 2005; Dahdouh-Guebas *et al*., 2005).

Storm surges can also flood mangroves in combination with sea-level rise may result in decreased productivity, photosynthesis, and survival (Ellison, 2000). Inundation of lenticels in the aerial roots can cause a decrease in oxygen concentrations in the mangroves, resulting in mass mortality (Ellison, 2006, 2015). Inundation is also projected to decrease the ability of mangrove leaves to conduct water and to photosynthesize (Naidoo, 1983).

Anthropogenic activities to the destruction of mangroves

Along with the climate change, different anthropogenic activities for the conversion of mangroves areas into agriculture, aquaculture, fisheries, along with resources collection have been a major threat to mangroves ecosystems (Alongi, 2002; Das and Mandal, 2016; Duke *et al*., 2007; IUCN, 1989; Primavera, 1997; Valiela *et al*., 2001). Regional sea-level rise is affected by tectonic movements that can cause land subsidence or uplift (Mandal and Bar, 2019). Anthropogenic activities that cause land subsidence through coastal development have been phenomenal. All the activities that have adverse effects on coastal areas include: 1) deficits in the sediment budget over the coastal surface, 2) shipping channels that cause bank erosion, 3) groundwater or oil extraction that causes submergence and, 4) dredging and mining that causes losses of land. The combination of global sea-level rise and local impacts is likely to cause land subsidence that threatens the existence of mangroves worldwide. However, mangroves need to adapt to changing sea-level for survival over long timescales. The aptitude of mangroves to adapt themselves to changing sea-level depends on the accretion rate relative to the rate of sea-level change (Alongi, 2008).

Mangrove resilience to sea-level rise

Mangroves have significant resilience to fluctuating sea level rise (Woodroffe and Grindrod, 1991) due to their ability to modify the environment through the processes of surface elevation change, as well as the ability for inland migration (Krauss *et al*., 2014). Thus, adaptation to global SLR is likely to be driven not only by local rates of SLR, but also by available sediment, local land uplift/subsidence and localized sediment auto-compaction (Krauss *et al*., 2014). The most common mangrove sedimentation trapping mechanism include: (1) reducing water velocities through aerial roots resulting into enhanced deposition of sediments (Furukawa and Wolanski, 1996); (2) microbial filamentous algal mats trapping and binding sediment; and (3) gathering of litter and woody debris. These mechanisms can lead to sediment accretion rates up to 20.8 mm yr^{-1} (Krauss *et al*., 2010; McKee *et al*., 2007).

Sundarbans a case study of mangrove loss

Asia shares the largest portion of global mangroves (41.9%) and the Sundarbans (Indian and Bangladesh together) is the largest single chunk of mangroves forest in the world (Table 1). Undivided Sundarban stretches from the Baleswar River of Bangladesh in the east to the Hooghly River of West Bengal in the west (Fig. 2 and 3). The total covered area is approximately 10,030 km^2, (Das and Jana, 2017) which is shared between Bangladesh (5770 km^2, 58%) and India (4260 km^2, 42%) (Gopal and Chauhan, 2006).

Sundarbans mangroves have been lost and distressed due to forest users for centuries. Besides, SLR is one of the major impacts of climate change on the coast of Sundarbans (Ali, 2000; CEGIS, 2006; Rasheed, 2008) followed by recurring cyclonic storms such as *Sidr* in 2007, *Aila* in 2009 (Das, 2012), *Fani* in 2019, *Bulbul* in 2019, etc. As a result, Sundarbans has been shrinking over the past few decades. In some parts of the Sundarbans, the sea is advancing about 200 yards a year (Hazra

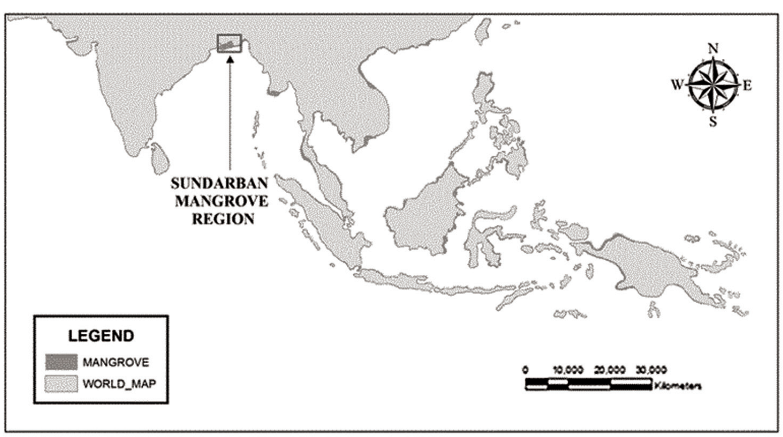

Fig. 2. *Sundarbans (India and Bangladesh together) mangrove region in SE Asia*

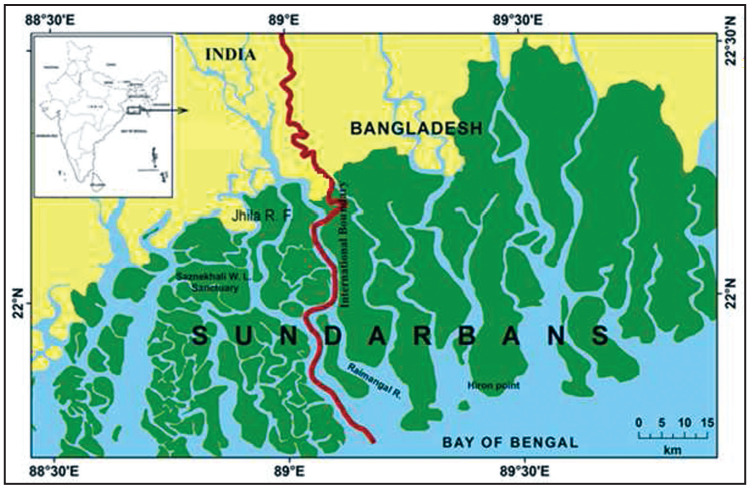

Fig. 3. *Undivided Sundarbans mangrove region (India and Bangladesh)*

et al., 2002). Forest Survey of India (FSI) report said that the mangrove cover in the Sundarbans has shrunk by more than 2 km^2 - from 2214 to 2112.11 km^2 between 2017 and 2019. Another study was done by the School of Oceanographic Studies, Jadavpur University using geoinformatics. According to them, from 1986 to 2012, 124.418 km^2 mangrove forest cover has been lost due to both natural and human causes.

However, a combination of SLR and tidal hydraulics often results in erosion of the sea face and estuary margins of Sundarbans. In the Indian Sundarbans, the overall erosion over the previous 30 years is estimated to be 162.879 km^2 (Hazra *et al*., 2017). Other similar studies in Bangladesh show that the erosion rate of eastern and western parts of the Sundarbans impact zone is 14 m yr^{-1} and 15 m yr^{-1} respectively. Consequently, from 1973 to 2010, the entire loss of land due to erosion was 233 km^2 (Rahman, 2012) (Table 1).

The calculation of relative threat from SLR for the Sundarbans mangroves is very complex, because, in Sundarbans five important processes are running instantaneously; such as tides, subsidence, coastal erosion, sediment accretion, and seal level rise due to global warming. These factors influence the mangrove region to a great extent so that the magnitude of areal loss remains unclear. The cumulative effect of these, described as relative mean sea level (RMSL), has risen between 3.14 mm yr^{-1} (Hazra *et al*., 2002) and almost 5 mm yr^{-1} (Nandy and Bandopadhyay, 2011) in the Sundarbans, which are much higher than global averages of 1.3 to 2 mm yr^{-1} (Dangendorf *et al*., 2017). According to IPCC, global mean sea-level rise is projected as up to 0.98 m or greater by 2100 and consequently 30-40% of coastal wetlands, as well as 100% of the global mangroves (Duke *et al*., 2007), could be vanished in the next 100 years. However, another well-known Lovelock model (Lovelock *et al*., 2015) advocates that the Sundarbans will persist beyond 2100 even under the most severe SLR scenario (1.4 m by 2100).

The present rate of sea-level change of nearby Diamond Harbour (22° 11' 34.91" N; 88° 11' 4.78" E) and Haldia (22° 4' 0.0228" N; 88° 4' 11.3124" E) tidal gauge station in Indian Sundarbans are estimated to about 4.67 ± 0.68 mm per year and 2.59 ± 1.00 mm per year respectively. From 1950 to 2014, the annual mean sea level has risen from 6.8 m to 7.23 m at Diamond Harbour, and from 1970 to 2014, has risen is about 6.92 to 7.17 m at Haldia (Pramanik, 2015).

But, other than SLR as well as land loss, the Sundarbans reserve forest (both in India and Bangladesh) is now showing signs of degradation. The extent and composition of mangroves in Sundarbans may undergo major change and land loss, depending on the rate of climate change and anthropogenic activities (Table 1). From 1873 to 1933, the mangrove forest was reduced to 6000 km^2 from 7500 km^2 (Blasco, 1977; Curtis, 1933;). Until then, the forest area in Bangladesh remained almost unchanged, but reclamation was started and forest cover has gradually declined in Indian Sundarbans. Vegetation inventories of Bangladesh's forest showed that the aerial extent of the tree coverage has been reduced by 0.04% per year during the period 1926/28-1995 (Iftekhar and Islam, 2004).

Over the past two decades, remote sensing techniques have played a vital role in mapping the spatio-temporal pattern of mangrove forests related to natural disasters and anthropogenic forces (Heumann, 2011). But, site-specific or micro-level studies in the Indian Sundarbans are not so encouraging; the majority deal with coastal geomorphic, sea-level rise and shoreline changes (Jayappa *et al*., 2006) only. Changes in vegetation dynamics are somehow neglected in these micro/meso-level studies.

Mangrove degradation study

In this scenario, an attempt has been taken for studying the health of the mangroves in Sundarbans instead of the complicated study of loss of mangrove only by sea-level rise or climate change. The widely used method for forest health study is the Normalized Difference Vegetation Index (NDVI). Most of the satellites which incorporate vegetation indices employ the mathematical relation to quantifying the growth density of the plankton earth surface; this mathematical relation is termed as NDVI.

The density of the green patch on the spatial platform is determined by the wavelengths of visible and near-infrared sunlight reflected by plants. With the passing of the white light through prism many different wavelengths make up the spectrum of sunlight. Some of the wavelengths are absorbed and some are reflected. The presence of chlorophyll pigments in the leaves absorbs the red and blue wavelengths but reflects the green wavelength, thus we perceive vegetation as green in colour. The leaves appear greener during the summer when the chlorophyll content is maximum, while in the autumn due to less chlorophyll the leaves reflect more red wavelength, causing it to appear red or yellow. The internal cell structure of healthy leaves strongly reflects the Near-Infrared portion of the spectrum ranging between 0.7 to 1.1 µm. being an excellent diffuse reflector (Bhatta, 2015). Thus the more the leaves present in a plant more will be the reflectance. NDVI is computed as,

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where, NIR and RED stand for the spectral reflectance measurements acquired in the near-infrared and red (visible) regions, respectively.

The result of the equation lies between the negative one i.e.(-1) to positive one i.e. (+1). Negative values of NDVI (values approaching -1) correspond to water. Values close to zero (-0.1 to 0.1) generally correspond to barren areas of rock, sand, or snow. Low, positive values represent shrub and grassland (approximately 0.2 to 0.4), while high values indicate temperate and tropical rainforests (values approaching 1) (Gerdzheva, 2014).

Two multi-temporal cloud-free satellite images (Landsat 4-5 TM C1 Level - I and Sentinel -2) covering whole or parts of the Sundarbans were downloaded from the freely available United States Geological Survey (USGS) (http://glovis.usgs.gov). The whole image processing procedure that includes layer stacking, mosaicking, and NDVI analysis was conducted using ERDAS Imagine 2014 software.

Multi-temporal satellite data of 2005 and 2018 were analyzed using an NDVI approach, where +1 represents dense vegetation areas, >0 and <+1 represents the vegetated areas, 0 represents the barren areas without vegetation and -1<=&<0 represents water. Our study shows that the number of pixels for vegetation in 2005 is 7848234 and for 2018, it is 7665320. The yearly rate of degradation of the forest is, therefore, around 0.113% comparing the two images. Sundarbans region is very much prone to tropical cyclones. These recurring cyclones such as *Sidr* in 2007, *Aila* in 2009, *Mora* in 2017 have resulted in the degradation of mangrove forests to a certain level, especially at the coastal margin. However, the mangrove's core region, generally able to withstand the severity of these catastrophic events, represents a progressive growth with dense canopy cover. So it is quite clear that the areal extent of the mangrove forest of the Sundarbans has not changed significantly in the last 14 years. An almost similar type of study was done by Giri *et al*. (2015) who found approximately 1.2% of forest lost during the last 25 years taking multi-temporal satellite data from the 1970s, 1990s, and 2000s using a supervised classification approach (Fig. 4).

Mangroves capability to sustain under climate change

Though little is known about the adaptive capacities of mangrove plants to cope up with the disturbances caused due to the change in the climatic scenario, Alongi (2008) has suggested some key attributes about the mangroves genetics that paves the way for its resilience in changing dynamics which are addressed below:

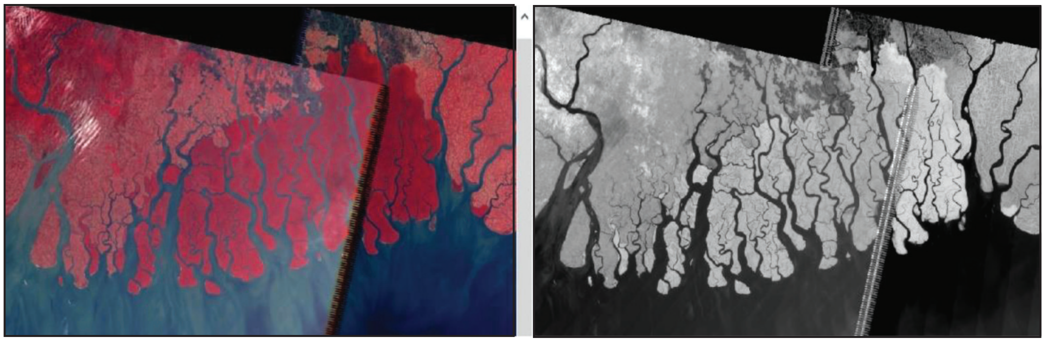

Fig. 4a. *Sundarbans (Indo-Bangladesh) NDVI (2005)*

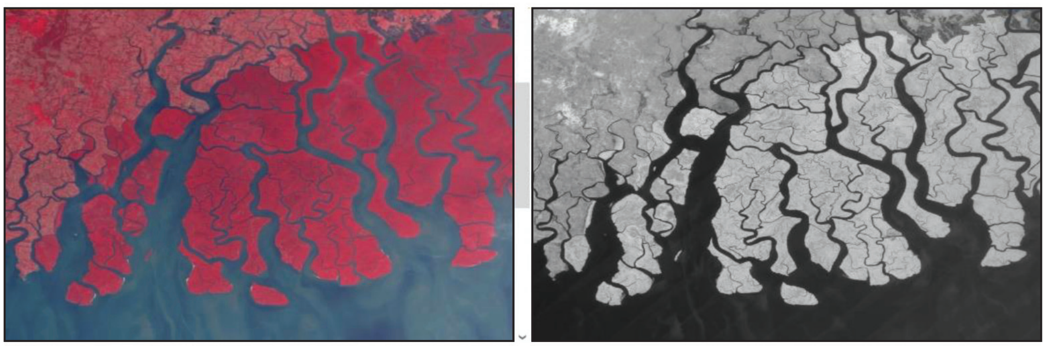

Fig. 4b. *Sundarbans core area (India) NDVI (2005)*

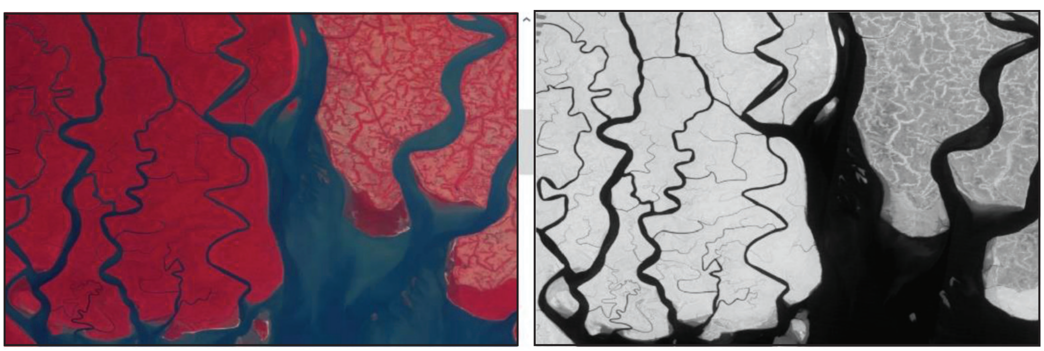

Fig. 4c. *Sundarbans core area (Bangladesh) NDVI (2005)*

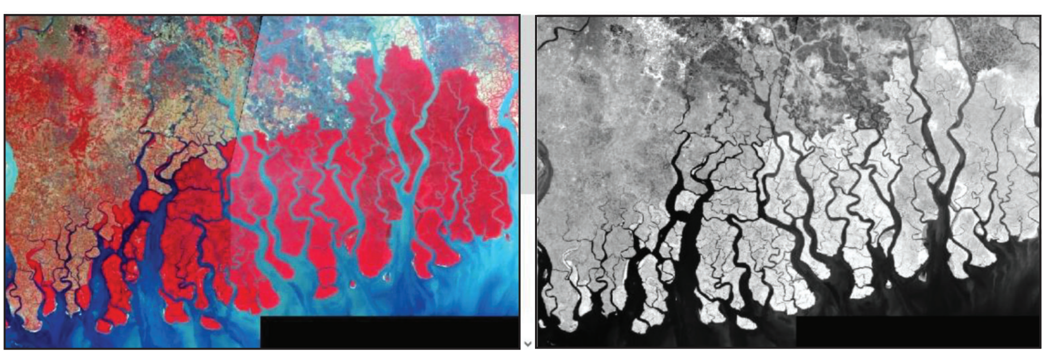

Fig. 4d. *Sundarbans (Indo-Bangladesh) NDVI (2018)*

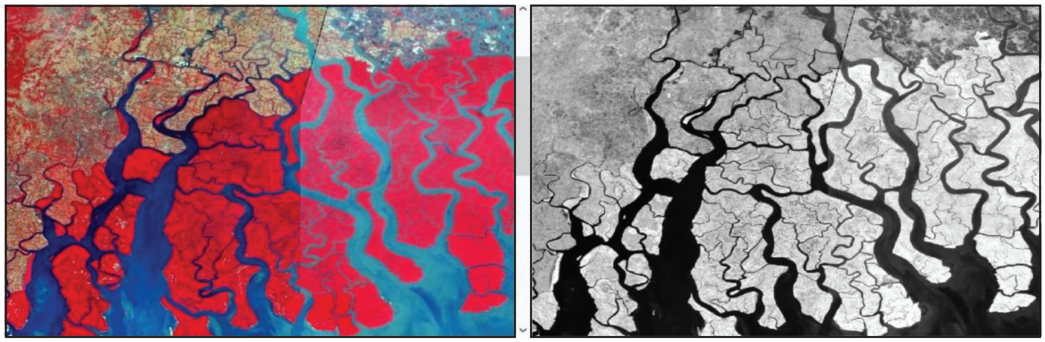

Fig. 4e. *Sundarbans core area (India) NDVI (2018)*

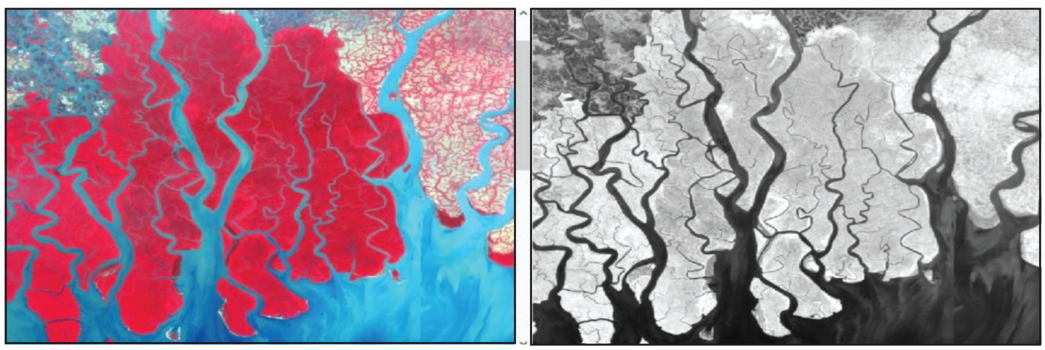

Fig. 4f. *Sundarbans core area (Bangladesh) NDVI (2018)*

- The loss of nutrients at the ground level is replenished at a very fast pace.
- Rapid biotic turnovers are facilitated by the nutrient flux and microbial decomposition.
- Self-reliance through genetics architecture leads to rapid rehabilitation and reconstruction of the diaphragm in the post calamity period.
- Forest skeleton and structure are being recovered in the post calamity period by virtue of species redundancy.
- Recovery of the diaphragm is also done by virtue of the accelerated rate of water circulation within the system.

Apart from all these inbuilt aspects, there are few factors suggested by Smith (1992) like temperature, salinity of water, frequency of tidal inundation, soil texture and soil anoxia and pH level in different micro and macro temporal and spatial extensions which also facilitate to pave the way for the sustainable attitude of mangroves in harsh climatic regions. However, the following methods can be inculcated in the areas of harshness in order to build up mangrove resilience.

- Delineating the vulnerable areas of climatic change and incorporate various strategic and protective measures, also finding out the areas which are capable of withstanding the harshness and start plantation of mangroves in those areas.
- It is impossible to counteract the natural climatic harshness but measures like alternative mangrove recruitment through natural or anthropological means can be done in susceptible areas for checking loss of biodiversity.
- Establishment of green mangrove belts or buffer zones in response to sea-level rise will ensure hassle free optimum land use land cover system in the adjacent areas.
- Incorporating effective measures like restoring and preserving the linkage between freshwater and sediments with mangroves also with the allied associate habitats like coral reefs hydras and seagrasses in the areas which have shown gallant valour in areas of harshness.
- Selecting mangrove species which are composing the following attributes like, i) tolerant to high

salinity, ii) resistant to strong winds, hurricanes, waves and tidal surges, iii) resilient to soil erosion, and iv) capable of reproduction at a fast pace.

In this juncture of the uncontrolled and untenable development process, it is a matter of deep concern that sea-level rise across the globe has caused one of the severe most threats to the coastal vegetation. But it is difficult to study the actual rise of the sea level, as well as the submergence of mangroves as the accretion of sediments, has also paved the way for the rise in the water level. Despite the resilient characters to have adaptability even in adverse environmental conditions, the growth of mangrove forests is not spared from the deadly paws of sea-level rise which scaled to 3.6 mm yr^{-1} between 2006 and 2015 (Lindsey, 2019). However, in the face of local sea-level rise, some regions, such as the Florida zone in the USA, will have the advantage of having more landward expansion as resilience means, whereas in more populated coastal regions like Sundarbans there is more likely to be the problem of reclamation or rehabilitation, thus restricting the inland migration of mangroves. Besides, owing to the global climate change average temperature and spatio-temporal variability increased the level of precipitation which in turn has accelerated the genesis of tropical cyclones. Hosting landfall of cyclonic storms has resulted in a degradation of mangrove species in the coastal areas, as a result the interaction of saline water with fresh water largely affected mangrove forests. Along with the above, in the third world countries dependence of the populace on the mangroves ecosystem for livelihood is a common scenario that may cause further degradation of mangroves in the context of changing climate – a situation to strangle mangroves to have severe stress, which is somewhat minimal in the developed world due to the remote existence and sufficient conservation.

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